INVESTIGATION OF AERODYNAMIC AND RADIOMETRIC LAND SURFACE TEMPERATURES

Project Summary / Final Report for grant NAG5-8679

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Introduction/Abstract

The surface temperature, T_s, of a land surface measured by a radiometer, $T_{s,r}$, and the temperature "felt" by the air, T_{aero}, often differ significantly and are difficult if not impossible to define rigorously. The relationship between $T_{s,r}$ and T_{aero} is often described using the parameter $kB^{-1} = \ln(z_0/z_{0h})$ where z_0 is the momentum roughness length of the surface, and z_{0h} is the scalar (temperature) roughness length of the surface. The project was undertaken in order to resolve this problem so that remotely sensed surface temperatures can be more readily used to predict sensible and latent heat fluxes from land surfaces.

The overall goal of the project was to reconcile the difference between $T_{s,r}$ and T_{aero}, while maintaining consistency within models and with theory and data. The project involved collaboration between researchers at Bucknell University, Boston University, University of Rhode Island, and the USDA/ARS Hydrology Laboratory. This report focuses on the work done at Bucknell, which used an analytical continuous-source flux model developed by Crago (1998), based on work by Brutsaert and Sugita (1996) to generate fluxes at all levels of the canopy. Named ALARM [Analytical Land-Atmosphere-Radiometer Model] by Suleiman and Crago (2002), the model assumes the foliage has an exponential vertical temperature profile. The same profile is felt by the within-canopy turbulence and "seen" by a radiometer viewing the surface from any zenith view angle. ALARM converts radiometric surface temperatures taken from any view angle into a clearly-defined version of T_{aero} called the equivalent isothermal surface temperature $T_{s,i}$, and then calculates the sensible heat flux H using Monin-Obukhov similarity theory [e.g., Brutsaert, 1982]. This allows remotely sensed $T_{s,r}$ measurements to be used to produce high quality sensible and latent heat flux estimates, or to validate or update the surface temperature produced by SVATs in climate or mesoscale models.

Methods/Goals

Goals

The project had three research objectives:

1. To investigate theoretical and conceptual differences among the formulations used for surface roughness, $T_{s,r}$ and T_{aero} among several models developed by the PI's.
2. To evaluate self-consistency and robustness of the models using field and remote sensing data, and to refine the treatments for $T_{s,r}$ and T_{aero} to provide better consistency between models, theory and data.
3. To examine the spatial scaling properties of these models and their ability to infer spatial variability of T_{aero} from spatial variations in $T_{s,r}$.

Methods

Work at Bucknell concentrated on developing the ALARM model into a robust method to convert $T_{s,r}$ measurements made at any zenith view angle into $T_{s,i}$ values which are then used to predict H. The work concentrated on grasslands, for which several high quality datasets are available (FIFE 1987 and 1989; SGP 1997; CASES 1997; HAPEX-Sehal). In particular, work focused on developing consistent parameterizations for variables describing the eddy diffusivity profile and the vertical profile of foliage temperature. A single parameterization was used to model sensible heat flux from each of these field experiments, including prediction of the spatial variability of sensible heat flux from the spatial variability of $T_{s,r}$. Accurate prediction of field observations was the primary method used to evaluate model performance.

Additional work, independent of the ALARM model, investigated the complementary relationship between actual and potential evaporation proposed by Bouchet (1968), and its use in estimating kB^{-1} independent of any surface temperature measurements.

Results

A number of outcomes have resulted:

1. Two key unknowns within ALARM have been parameterized. The ALARM parameterization has as its key unknowns the foliage temperature at the canopy top, the soil surface temperature, and the exponential decay constant of the foliage temperature profile. With a single measurement of $T_{s,r}$, only one unknown can be determined, leaving two to be parameterized. In Suleiman and Crago (2002), a parameterization of b in terms of canopy density was developed. In Crago and Suleiman (2003) the parameterization was refined, and the foliage temperature at the canopy top was parameterized as the temperature found by extrapolating the surface sublayer temperature profile down to the top of the canopy.
2. The ALARM model has been tested, using the parameterization described above in Result 1, using multiple datasets collected from grassland sites. Results are given in Table I and, for CASES, in Figure 1 (from Crago and Suleiman, 2003)
3. Spatial variability of remotely-sensed land surface temperature was used to infer spatial variability of sensible heat fluxes. Because of inter-site differences in canopy density, view angle, and surface energy transport processes, radiometric surface temperatures are not directly related to the sensible heat fluxes. Therefore, ALARM was used to convert from radiometric to equivalent isothermal surface temperature. Remotely-sensed (NS001 and TIMS) radiometric surface temperatures from the FIFE experiment on 5 days in 1987 and 1989 were used. The dataset was compiled by Qualls and Hopson (1998). Figure 2 shows the results for August 4, 1989, and Table II shows the results from this and the remaining days. In general, ALARM best captured the spatial variability of H on days having the greatest variability in measured H (i.e. standard deviation of H_r).
4. Incorporation of the ALARM scalar roughness parameterization into the complementary approach for evaporation. In the advection-aridity formulation of the complementary approach [Brutsaert and Stricker, 1979], the availability of surface moisture is inferred from the dryness of the air, which requires the estimation of the "drying power" of the air. When applied to short time scales (on order of 10 to 60 minutes), the estimation of drying power depends on kB^{-1} [Crago and Crowley, 2003a]. Data from FIFE, SGP, HAPEX-Sahel, and CASES were used to test the advection-aridity equation with kB^{-1} determined from the ALARM formulation. Results are shown in Figure 1. Five other complementary formulations were also tested, including one introduced by Granger [1989]. Only

these two formulations consistently produced relatively reliable results [Crago and Crowley, 2003a].

5. A new method was developed to estimate kB^{-1} from field data collected by R. Qualls at the CASES 97 experiment. The method uses the complementary evaporation equations (specifically, the advection aridity method) to give an alternative expression of kB^{-1} or z_{0v} independent of the measurement of surface variables (Crago and Crowley, 2003b). Key results were that as canopy height and density increase (at least in the ranges observed: $1.13<LAI<1.79$) the transport efficiency of water vapor increases more rapidly than the transport efficiency of momentum (Crago and Crowley, 2003b). This basic result is supported by the theoretical canopy transport model results of Brutsaert (1979) as presented in Brutsaert (1982), in which less dense canopies such as grass had larger kB^{-1} values than those for an aspen forest.

Conclusions

Reseach at Bucknell University funded under this grant has lead to the following conclusions:

1. The ALARM model is robust enough to provide reasonable sensible heat flux estimates from several grassland sites with LAI's ranging from less than 0.5 to 4, without tuning of parameter values.
2. The scalar roughness parameterization is important in the complementary approach at short time scales, and the ALARM model results in reasonable estimates of evaporation when used specifically in the advection-aridity equation.
3. The advection-aridity equation can be used to estimate kB^{-1} from field data. The behavior of kB^{-1}, which was found independent of any measurements of surface conditions, is supported by previous theoretical work.
4. Methods that simultaneously solve the energy budget, mass transport, and sensible heat transport equations for the canopy (e.g., Friedl, 1995; 2002; Kustas and Norman, 1997; 1999) have a definite advantage over methods that solve for sensible heat flux independently of the other components of the energy budget, such as ALARM. In particular, the latter methods do not prevent occasional large errors, because they are not constrained to balance the energy budget.
5. The ALARM model with the parameterization by Crago and Suleiman (2003) is computationally simple, does not require data regarding moisture availability or stomatal resistance, and typically results in RMS errors of H within 35 W m^{-2}, when used with ground-based radiometers.

Impacts

The land surface models under investigation at Boston University, the ARS Hydrology Lab, and at Bucknell University (the ALARM model), can be used, in combination with remotely-sensed surface temperatures and LAI, to collect global datasets of energy budget components. They may also aid in assimilating remotely sensed surface temperatures into mesoscale and global weather and climate models. Without such models to correct for the difference between radiometric and aerodynamic surface temperatures, large errors in the datasets and assimilated data are likely.

Graphics and Tables

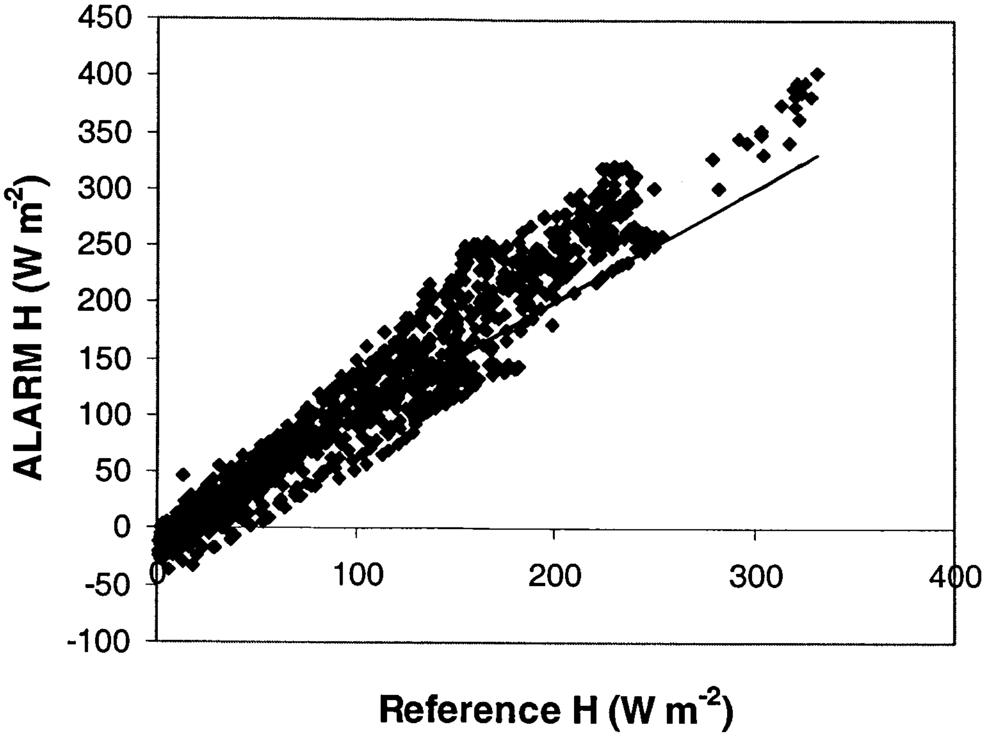

Fig 1. Results of the ALARM parameterization from the CASES dataset (from Crago and Suleiman, 2003).

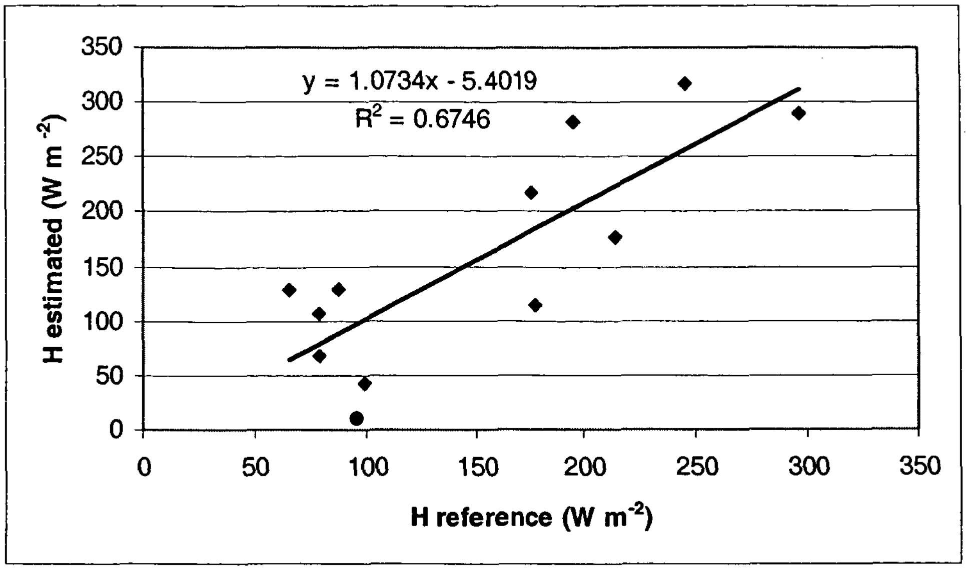

Figure 2. Spatial variability of sensible heat flux at FIFE on August 4, 1989, estimated from TIMS radiometric surface temperatures with the ALARM model.

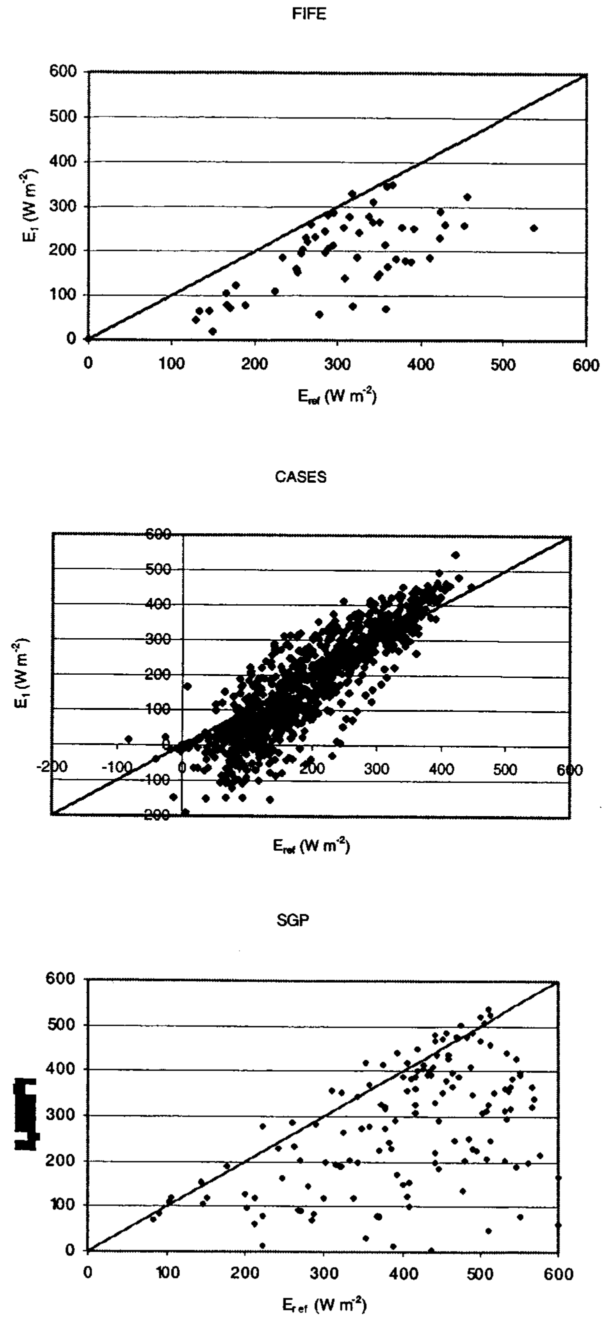

Figure 3. Latent heat flux E_1 calculated with the advection-aridity formulation using ALARM for kB^{-1}, plotted against measured values E_{ref} for the FIFE, CASES and SGP experiments (Crago and Crowley, 2003a); plot for Sahel data not included here.

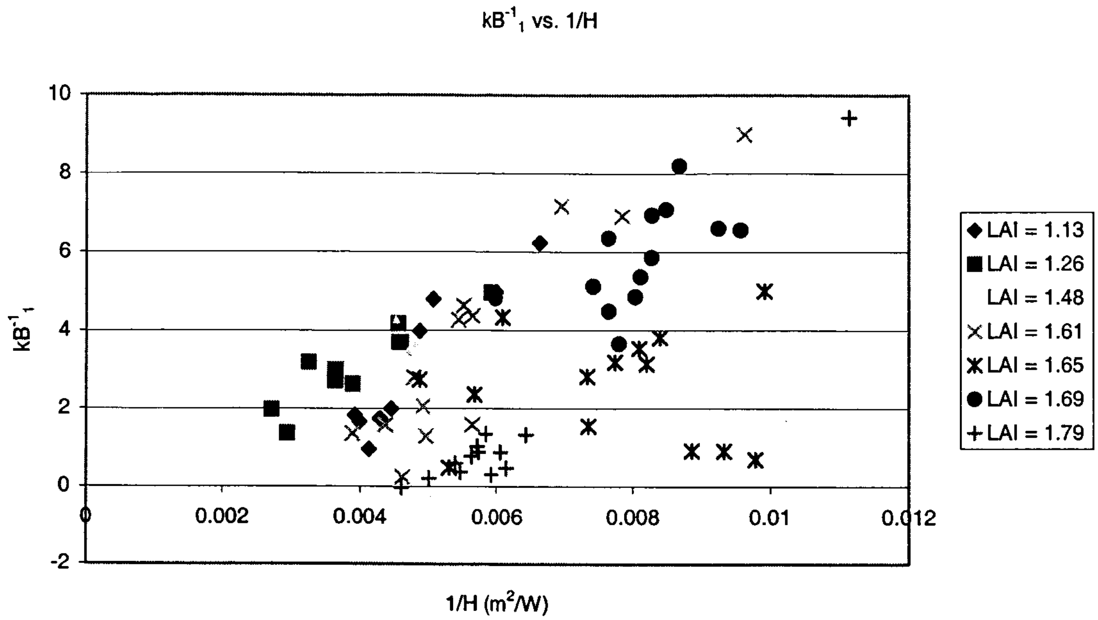

Figure 4. The value of kB^{-1} calculated from the advection-aridity approach plotted as a function of 1/H. Different shapes and colors of data markers indicate the value of the leaf area index.

Table I. Summary of comparisons between H estimated with several models and the measured (reference) values, H_r. $\Sigma H/\Sigma H_r$ is a bias measurement consisting of the ratio of the sum of model-predicted H to the sum of H_r. Estimates are given from the ALARM (Crago and Suleiman, 2003), Lhomme et al. (2001) and Massman (1999) models.

Site	Model	R^2	Regression for H (W m^{-2})	RMS error (W m^{-2})	$\Sigma H/\Sigma H_r$
CASES	ALARM	0.93	$1.26H_r$-18.1	34.8	1.11
	Lhomme	0.90	$0.84H_r$-10.9	37.9	0.75
	Massman	0.9	$1.21H_r$-17.9	31.7	1.06
FIFE	ALARM	0.85	$1.27H_r$-49.0	34.7	0.944
	Lhomme	0.73	$1.07H_r$-21.5	39.0	0.927
	Massman	0.78	$1.41H_r$-43.3	52.2	1.12
SGP	ALARM	0.86	$0.88H_r$-17.8	34.0	0.65
	Lhomme	0.68	$0.97H_r$-25.2	45.2	0.64
	Massman	0.76	$0.75H_r$-20.0	47.5	0.49

Table II. Statistics comparing spatially-variable ALARM estimates of H with field-measured values (H_r) for the five golden days at FIFE.

Date	R^2	RMS error (W m^{-2})	Standard deviation of H_r (W m^{-2})
June 6, 1987	0.25	71	43
July 11, 1987	0.44	*322	69
August 15, 1987	0.13	71	43
October 11, 1987	0.30	93	66
August 4, 1987	0.67	55	77

* Calibration of $T_{s,r}$ measurements uncertain.

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